Biofuel
Promised Land or Mirage?(*)

And other musings on bio-fuel, sustainable transportation and energy

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(*) both involve a lengthy walk in the desert
Education
• Ch.E. Degree – Padova, Italy
• Ph.D. – Ch.E.– Imperial College, London UK

Professional
• Shell Research
• Cray Research
• Cargill
• The wilderness of start-ups…
Chemical engineering in a nutshell

• Inlet – Outlet + Production – Consumption = Accumulation
  – Corollary 1: The above applies to mass AND money
  – Corollary 2: If Accumulation of money is <= 0 investors are unhappy
  – Corollary 3: (recently stated) Uncle Sam will not correct 2 forever

• Regardless of what many think, thermodynamics are NOT an opinion
  – Corollary: Eventually applies also to people on Sandy Hill and Foggy Bottoms

• Mass balances in moles were not just an invention to drive student crazy
  – Corollary: They work pretty well though on that too…

• The world is a complex system: non-linear, dynamic and full of lags and feedback loops… deal with it.

“All models are wrong, some are convenient”.
Prof. George Box
Talking about energy is fraught with intellectual and semantic risks...

What is energy efficiency?
Which one is more energy efficient?

** IT DEPENDS! **

(* typical weasel answers given by engineers to fudge tough issues or escape admitting ignorance)
The answer is: it depends.

0.13 mpg @ 500 mph

40 mph @ 60 mph

Gallons per passenger mile

400 passengers in a 747 -> 0.019
Lone commuter in a Prius -> 0.025

We do not care about energy. We do care about energy services. We do not purchase fuel.
We purchase mobility
## Distribution of energy use by source (source US Dept of Energy)

<table>
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</table>
Evolution of car registrations.

Source: US DOE Transportation Energy Data Book
Evolution of air transportation.

No foreseeable alternative to liquid fuel for aviation

Source ATA-ICAO
Sustainable transportation is not optional

- Personal mobility one of the most distinctive conquests of the modern society. Is one of the most coveted goals of people worldwide as they gain increased affluence.

- Access to inexpensive and widespread mobility for goods and people essential to the unprecedented economic growth of the XX century and its continued expansion in the XXI century.

- We can’t deny to so much of humankind the benefits the western world had for so long.

- A world without affordable transportation is going to be a socially and economically grim one.

- A world without sustainable transportation is going to be an environmentally grim one.

Delivering access to sustainable and affordable mobility is one of the defining challenges of the XXI century.
Biofuels to the rescue?
Biofuels, an emotional topic between righteous but often misinformed outrage....
and triumphant but often incomplete and misleading marketing or pandering
Biofuels are a wide range of fuels which are in some way derived from biomass. The term covers solid biomass, liquid fuels and various biogases. Biofuels are gaining increased public and scientific attention, driven by factors such as oil price spikes and the need for increased energy security.

Any fuel that is obtained from a renewable biological resource, especially from biomass

A form of renewable fuel that’s derived from biomass, which includes organic materials produced by plants, animals or microorganisms.

Gas, such as methane, or liquid fuel, such as ethanol (ethyl alcohol) made from organic waste material, usually by microbial action.

Fuels devised from biological materials including crops (especially trees) and animal wastes

Gas or liquid fuel made from plant material (biomass). Includes wood, wood waste, wood liquors, peat, railroad ties, wood sludge, spent sulfite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, other waste, and ...

Fuels that are generated by solar energy and photosynthesis, either on an annual basis (crops, grasses, etc.) or over a period of a number of years (trees). Biofuels do work, but the scale of use is the main issue with them, since our overconsumption cannot be met with biofuels. ...

A biofuel is liquid or gaseous product that can be used in the internal combustion engine of a transportation vehicle. It is notable in that it contains a percentage of renewable products produced from plant or animal sources. ...

A fuel produced from dry organic matter or combustible oils produced by plants. Examples of biofuel include alcohol (from fermented sugar), black liquor from the paper manufacturing process, wood, and soybean oil.

Any fuel that is derived from biomass — recently living organisms or their metabolic byproducts — from sources such as farming, forestry, and biodegradable industrial and municipal waste. See renewables.

is any liquid, solid or gas fuel refined in whole or in part from sustainable biological materials, usually plants. Some biofuels, like ethanol, are refined from food plants such as corn, but technologies are being developed to use nonfood plants and crop residue from food plants.

Fuels such as ethanol and diesel produced from sugars, vegetable oils, or other organic matter using biotechnology methods.
Strategies for Biofuel Production

Biomass Feedstocks
Cellulosic Biomass (wood, wood wastes, corn stover, switch grass, agricultural waste, straw, etc.)
Chemical Structure: cellulose, hemicellulose, lignin

Corn Stover
Bagasse
Corn Grain
Sugarcane

Triglycerides (Vegetable Oils, Algae)

Gasification
CO + H₂

Syn-gas
Water-gas shift
MeOH Synthesis
Fischer-Tropsch Synthesis

Steam-Reforming

Alkanes

Fast Pyrolysis
Liquefaction

Bio-oils (Sugars, Acids, Aldehydes, Aromatics)

Hydrodeoxygenation
Zeolite Upgrading
Emulsions

Aromatics, hydrocarbons
Aromatics, light alkanes, coke

Direct Use

Lignin (coumaryl, coniferyl and sinapyl alcohols)

C₅ Sugars (Xylose)

Dehydration

Furfural

Aqu. Phase Proc.
MTHF (Methyltetrahydrofuran)

Dehydration

C₆ Sugars (Glucose, Fructose)

Levulinic Acid

Esterification
Levulinic Esters

Hydrogenation

Ethanol, Butanol

C₈-C₁₃ n-Alkanes, Alcohols

Hydrodeoxygenation

C₁₂-C₁₈ n-Alkanes

Zeolite

Direct Use

C₁-C₆ n-Alkanes

APD/H

Aromatics, alkanes, coke

Zeolite

Blending/Direct Use

Key: Black - Chemical Conversion
Green - Biological Conversion
Blue - Both Chemical & Biological Conv.

Triglyceride (TAG) structure
TAG structure and fuels.

FOG = biogenic fats, oils and greases

- FOG
- Typical Veg. Oil
- Diesel Fuel
- Gasoline
- Jet Fuel

Carbon Number
Hydrotreating of lipids over Ni/Mo catalysts

Rx: saturated or mono/polyunsaturated aliphatic chain (typically C14-C18)

+1 ½ H₂ Backbone cleavage

+ ½ H₂ - Decarboxylation

+ H₂ according to unsaturation level

Isomerization and Hydrocracking to control cold flow properties and carbon chain distribution

CH₂—O—C—Rx

CH—O—C—Rx

CH₂—O—C—Rx

+ 3 •O—C—Rx

CH₂

CH₂ + 3 •O—C—Rx

CH₃

CH₂ + 3 ½ H₂ Hydrodeoxygenation

Rx → CH₃ + 2H₂O

Rx → H + CO₂

Cₙ/Cₙ+1
Renewable paraffins

\[
\% \text{ decarboxylation} = \frac{\Delta n-C_{17}}{\Delta n-C_{17} + \Delta n-C_{18}} = 64\%
\]
Renewable fuels cost structure. It is a feedstock game!

Production Costs per Gallon of renewable jet fuel

- Feedstocks 81%
- Hydrogen 2%
- Utilities 2%
- Production Overhead 2%
- Interest & Depreciation 6%
- Licensing Fee 2%
- Target ROE on Plant 5%

Current crop oil price

Production Costs per Gallon

- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1
- 1.1

$/bbl

$/lb
Algae promise: Large lipids (vegetable oil) production

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<tr>
<td>Algae</td>
<td>5000-15000</td>
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</table>

Oil yields

Source unknown, but widely used table. It is on the Internet so must be true.
The pitfalls of algae

Algae are deceptive because they are very good at pigment production.

Even in best conditions (much) less than 1 gram (db) biomass per liter!

Physical and biological processes prevents higher concentrations.

Key differences with conventional crops:
- Dilution
- Fast growth requires continuous harvesting
- Storage is not viable
- Nutrient delivery
What are the realistic biomass yields?

- It starts with solar radiation

- Only 45% of solar radiation is photosynthetically active (PAR)

- The **maximum theoretical and thermodynamically limited** conversion of PAR into biomass is 27%

- **Hence the maximum theoretical yield of solar irradiation into biomass energy is 12%**
  - In real life most common <1%
  - highly productive corn hybrids are ~1% aiming to 3 to 4%
  - 5 to 10% may be possible in future but not without extensive use of genetic engineering

- Under these conditions it becomes difficult to reconcile some of the large yield numbers that are proposed….

- For comparison PV efficiency are:
  - PV cells ~ 10-15%
Example of biomass production potential – we get back to this later...

World map of algae biomass productivity (t ha\(^{-1}\) year\(^{-1}\))
(at 10% photosynthetic efficiency and 23 MJ kg\(^{-1}\) dry biomass)

... and remember 10% efficiency is REALLY good.....
Best US potential – US Southwest

- 141 t/ac
  - 74 t/ac of C -> 271 t/ac of CO2
  - 11.2 t/ac of N -> 24 t/ac of Urea (CH4N2O2)
  - 380 kg/ac of P -> 1.8 ton/ac of Ammonium Phosphate (H12N3O4P)
    - Slightly reduces stoichiometric need of ammonia

<table>
<thead>
<tr>
<th>Proximate analysis (wt. %)</th>
<th>Ultimate analysis (wt. %)</th>
<th>Elemental analysis (mg/kg sample (dry))</th>
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<td>Water</td>
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<td>Calorific value (kJ/kg)</td>
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<td>Total:</td>
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Algae biomass composition example. Source: Phyllis Database
Productivity in controlled lab conditions of some non-gmo alage strains

<table>
<thead>
<tr>
<th>Microalgal species</th>
<th>Biomass productivity (mg L(^{-1}) day(^{-1}))</th>
<th>Lipid content (% biomass)</th>
<th>Lipid productivity (mg L(^{-1}) day(^{-1}))</th>
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<tr>
<td><em>Porphyridium cruentum</em></td>
<td>613.3 ± 77.8</td>
<td>9.4 ± 0.2</td>
<td>57.5 ± 7.3</td>
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<td><em>Tetraselmis suecica OR</em></td>
<td>448.0 ± 0.0</td>
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<td><em>Tetraselmis sp. LW</em></td>
<td>414.0 ± 11.3</td>
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<td>61.8 ± 1.7</td>
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<td><em>Tetraselmis suecica CV</em></td>
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<td><em>Chlorococcum sp. UMACC 112</em></td>
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<td><em>Chlorella sorokiniana</em></td>
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<td><em>Chlorella sp. AMI2</em></td>
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<td>20.6 ± 0.8</td>
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<td><strong>Nannochloropsis sp. RM</strong></td>
<td>278.2 ± 0.0</td>
<td>31.0 ± 0.5</td>
<td>86.3 ± 0.0</td>
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<td><em>Elipsochlora sp. LW 277/01</em></td>
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<td><em>Nannochloropsis sp. MRS</em></td>
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<td><em>Scenedesmus quadricauda</em></td>
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<td><em>Monodus subterraneus UTEX 151</em></td>
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<td><em>Isochrysis T-ISO</em> CS 177*</td>
<td>252.5 ± 1.8</td>
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<td><strong>Nannochloropsis sp. ZM</strong></td>
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<td>33.1 ± 1.7</td>
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<tr>
<td><em>Pavlova salina</em></td>
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<td><strong>Nannochloropsis sp. RP</strong></td>
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<td><em>Nannochloropsis sp. CS 246</em></td>
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<td><em>Chlorella vulgaris CCAP 211/11b</em></td>
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<td><em>Pavlova lutheri</em></td>
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<td>78.9 ± 3.9</td>
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<td><em>Isochrysis sp. MRS</em></td>
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<td>28.7 ± 0.5</td>
<td>55.6 ± 1.6</td>
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<td><em>Thalassiosira pseudonana</em></td>
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<td><em>Skeletonema sp. CS 252</em></td>
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<td><em>Skeletonema sp. CS 181</em></td>
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<td><em>Chaetoceros muelleri</em></td>
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<td><em>Chaetoceros calcitrans</em></td>
<td>62.0 ± 1.4</td>
<td>40.9 ± 0.1</td>
<td>25.3 ± 0.6</td>
</tr>
</tbody>
</table>

<<1% ds
Note the tradeoff between total biomass and lipid yields

Source: Prof. Mario Tredici
University of Florence, Italy
How that translates in oil productivity per acre?

- Say: 86 mg/lt/day productivity of oil
  - Algae grow in the small layer where light can penetrate, around 10 cm depth
  - Hence 8.6 gr/m2/day of oil
    - Biomass is 28 gr/m2/day
  - Over a year that translates into this oil production:
    - 28,260 lt/ha/yr
    - 3026 gal/ac/yr

This under the best laboratory conditions! Challenging to be easily and consistently reproduced in large scale.
Reality check! Thermodynamics are not an opinion!

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Still good, but where, at which cost and what are the challenges
Basic flow diagram of micro-algae processing

Primary harvesting step

Concentration, may include more than one step. More than 20% ds unlikely without physical disruption of cell wall structure and drying

May require drying to get to oil concentration high enough for oil extraction. May require additional treatment step to disrupt cell wall structure and facilitate separation

Current oil extraction approaches (e.g. solvent extraction) work fine but not optimal for relatively low fat content. We need to reduce the need for drying.
A little exercise to visualize and quantify dilution impact on cost

A regulation Olympic pool
50 m x 25 m x 2 m
2,500,000 liters
661,375 gallons
Now that we know how much water we have…

- Let’s assume:
  - That the same amount of water in an Olympic pool is used in a raceway pond 50 cm (1.6 ft) deep
    - That is a growing area of 5000 m² or 1.27 ac
  - Very good – but not impossible - productivity values
    - 20 g/m²/day
    - 30% lipids

- That means:
  - 100 kg (220 lb) of biomass per day
  - 33 l (8.7 gal) of oil per day
  - 2,500 gal/ac of oil yield

In order to produce 8.7 gal of oil we need to process 661,000 gallons of water EVERY DAY
Some back of a small envelope calculation

- **Pumping cost for 661,000 gpd**
  - Pumping cost ($/hr) = 0.746 * F_gpm * H_ft * P_cost/(3960 * E_p*E_m)
  - Assuming:
    - $0.07/kWh
    - 10 ft head
  - $1.80/day or $0.20/gal of oil
  - Net of capital cost

- **Primary concentration**
  - 661,000 gpd to 1322 gpd
  - Ignore costs and energy demand

- **Secondary concentration**
  - 1322 gpd to 500 gpd
  - Centrifugation of 1322 gpd
  - 500 gpd product (20% ds)
  - 1/3 to 2/3 hp centrifuge
  - $0.07/gal of oil
  - Net of capital cost

- **Dewatering**
  - 500 gpd @ 20% ds
  - 6% oil content
  - Remove enough water to be at 10% oil, 72 gpd
  - 72 gpd -> 582 lb of water @ 1000 BTU/lb -> 582,000 BTU/day
  - Assuming gas at $4/MMBTU
  - $2.32/day or $0.26/gal of oil
  - Net of capital cost and efficiency factors

In this extremely simplified circumstances already the processing cost is > $0.50/gal

Energy inputs:
- 256 kWh/day
- Energy yield of oil:
  - 307 kWh/day

2/3 of oil energy already lost!
Detailed numbers indicate that a <$1.00/gal facility is nowhere insight

### Economic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired rate of return</td>
<td>10.00%</td>
</tr>
<tr>
<td>Depreciation years</td>
<td>10</td>
</tr>
<tr>
<td>Analysis Period (years)</td>
<td>20</td>
</tr>
<tr>
<td>Tax Rate</td>
<td>40.00%</td>
</tr>
<tr>
<td>Capital Recovery Factor</td>
<td>0.117</td>
</tr>
<tr>
<td>Present Value Depreciation</td>
<td>0.614</td>
</tr>
<tr>
<td>Fixed Charge Rate</td>
<td>0.148</td>
</tr>
</tbody>
</table>

### Algae Pond Operational Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pond Depth cm</td>
<td>20</td>
</tr>
<tr>
<td>Single Pond Area ha</td>
<td>10</td>
</tr>
<tr>
<td>Evaporation Rate cm/day</td>
<td>0.691366243</td>
</tr>
<tr>
<td>Area Productivity g/sq m-d</td>
<td>10.93990123</td>
</tr>
<tr>
<td>Pond Algae Concentration g/l</td>
<td>0.3834736</td>
</tr>
<tr>
<td>% Lipid Content</td>
<td>15%</td>
</tr>
<tr>
<td>Total Pond Area (incl 10 ha)</td>
<td>1,000</td>
</tr>
<tr>
<td>Single Pond Flow lpd</td>
<td>2,809,805</td>
</tr>
<tr>
<td>Total Pond Flow lpd</td>
<td>280,980,491</td>
</tr>
<tr>
<td>Pond volume liters</td>
<td>20,000,000</td>
</tr>
<tr>
<td>Retention Time days</td>
<td>7</td>
</tr>
</tbody>
</table>

### Other Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Cost</td>
<td>$0.00</td>
</tr>
<tr>
<td>Power Plant Recov CO2</td>
<td>$50.46</td>
</tr>
<tr>
<td>Cost oper mt</td>
<td>$50.46</td>
</tr>
<tr>
<td>Natural Gas Price per MMBtu</td>
<td>$6.57</td>
</tr>
<tr>
<td>Soy meal price per mt</td>
<td>$203.38</td>
</tr>
<tr>
<td>Land Price per acre</td>
<td>$3,000.00</td>
</tr>
<tr>
<td>Total to Pond Acres</td>
<td>1.50</td>
</tr>
<tr>
<td>Water Price per acre-ft</td>
<td>$2.08</td>
</tr>
<tr>
<td>Water Price per cu m</td>
<td>$0.018</td>
</tr>
<tr>
<td>Kadam (1997) cost</td>
<td>$40.00</td>
</tr>
<tr>
<td>Inflation adjusted</td>
<td>$49.46</td>
</tr>
</tbody>
</table>

### Other Values

<table>
<thead>
<tr>
<th>$2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Biomass Production</td>
</tr>
<tr>
<td>Total Oil Production</td>
</tr>
<tr>
<td>Total Capital</td>
</tr>
<tr>
<td>Total Operating Cost</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capital per Annual Gallon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil (gal)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Operating Cost</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
<tr>
<td>Credit Algae Coprod</td>
</tr>
<tr>
<td>Credit Elec</td>
</tr>
<tr>
<td>Net Cost</td>
</tr>
</tbody>
</table>

- CO2 from flue gas
- Dedicated algae ponds
- Primary dewater: belt filter
- Secondary dewater: centrifuge
- Drying natural gas
- Hexane solvent extraction

**Basic economics of a facility for 1.5 Mgal/yr**
(sources: John Sheean – U of MN and Ben Wu – Sandia National Labs)
The biomass dilemma

- Liquid fuel (e.g. cellulosic ethanol)
- Power
The biomass dilemma

Biomass

1 dry ton
$80
16,800 MJ

Chemical Conversion

~ 50 gge
686 kg of CO2

Combustion

~ 0.8 tce
2,040 kg of CO2

Oil

70 gal EtOH
9,960 MJ
$210 @ $3/gal/
60% eff.

Liquid Fuel

~ 50 gge
686 kg of CO2

Cars (LDV)

1,400 kWh
5,100 MJ
$98 @ $0.07/kWh - 30% eff.

Combustion

~ 0.8 tce
2,040 kg of CO2

Power

Grid

Users

gge=gallons of gasoline equivalent
tce=tons of coal equivalent

Coal
Fuel is only a component of a transportation system

BIOMASS POWERED!
The biomass dilemma

Cost of CO2

- $20/tonne
- 1 gal of gasoline (~3.0 $/gal) -> 8.8 kg of CO2 -> $0.17/gal (+5.8%)
- 1 ton of coal (~55 $/ton) -> 2,547 kg of CO2 -> $50.1/ton (+100%)

(Bio) Chemical Conversion

Liquid Fuel

Cars (LDV)

1 dry ton
16,800 MJ

1990 MJ
20% dte
11% ese
$0.10/MJ

70 gal EtOH
9,960 MJ
$210 @ $3/gal/
60% eff.

1,400 kWh
5,100 MJ
$98 @ $0.07/kWh - 30% eff.

~ 50 gge
440 kg of CO2

~ 0.8 tce
2,040 kg of CO2

(16,800 MJ)

Combustion

Power

Grid

Users

dte = drive train efficiency
ese = energy service efficiency
Things may not be better with “advanced” biofuels….

One kg of glucose can give us:

- **Ethanol**
  - \( \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 2 \text{CH}_2\text{H}_2\text{OH} + 2 \text{CO}_2 \) (0.51/0.49) 14.72 MJ, 0.64 lt

- **Butanol**
  - \( \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{C}_4\text{H}_9\text{OH} + 2\text{CO}_2 + \text{H}_2\text{O} \) (0.42/0.48/0.1) 13.84 MJ, 0.51 lt

- **n-Octane**
  - \( \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 0.48 \text{C}_8\text{H}_{18} + 2.17 \text{CO}_2 + 1.63 \text{H}_2\text{O} \) (0.30/0.53/0.17) 13.33 MJ, 0.42 lt

- **Ethylbenzene**
  - \( \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 0.57 \text{C}_8\text{H}_{10} + 1.42 \text{CO}_2 + 3.14 \text{H}_2\text{O} \) (0.33/0.34/0.31) 13.50 MJ, 0.38 lt
Rethink the assumptions....

Production and transformation systems can be very distant in high energy density systems
They need to be closer when the energy density is lower
Energy in a barrel of oil....

1 barrel of oil equivalent (boe)
6.1 GJ
Ideal biomass production potential with algae

World map of algae biomass productivity (t ha$^{-1}$ year$^{-1}$)
(at 10% photosynthetic efficiency and 23 MJ kg$^{-1}$ dry biomass)

1 ha = 2.47 ac
• About 10 tons db per year per acre
  – Based on average 150 bu/ac of corn (56 lb/bu @ 15% moisture)

• Theoretical energy availability
  – Heating value ~ 8000 lbu/lb, dry basis
  – 168 MMBTU/ac or 177 GJ (30 boe)

• Typical constraints
  – Biomass 15% to 30% moisture at harvest. More if left on the ground longer
  – Max 50% of biomass available to preserve soil health
  – High bulk density (3 lb/cft)
Which path to follow?

• Sustainable transportation should be addressed from a comprehensive point of view that includes the whole supply chain including the demand side

• Technology advances, need to be evaluated across the whole supply chain
  – New feedstock, new molecules, new drive trains, new transportation options
  – By reducing liquid consumption we can meet blending level with lower volumes

• Societal factors are important.
Societal factors?....

- Land usage and global resources
  - Food vs. fuel
  - Water and land disposition
  - Fossil fuels dependency of global agricultural system
  - Phosphorus and nitrogen supply

- Actual carbon footprint
  - De-carbonization of the economy
  - LCA approaches

- Energy independence diversification and energy policy goals
  - Transportation policy
  - Public vs. Private

- Societal and human issues
  - Urban development
  - Personal freedom
  - Work attitudes
A possible path forward for biofuels

- Biofuel R&D should focus in the area where the need of a high density liquid fuel remains critical and "electrons" cannot be a replacement.

- We cannot win on the supply side alone.

- The need of gasoline blending stock remains, but is moderated by the reduction in consumption and the trend towards electrification.

- As the overall volume is nonetheless increasing we need to have better integration with the existing energy infrastructure.

- Biofuels needs to be valued by their energy value and not by the volume.

- Key sectors: Aviation Fuels and HDV (aka large trucks)
  - Jet Fuel (Kerosine) and Diesel
  - Middle distillates (C10-C22 range)
  - Strong and growing demand especially in BRIC economies
  - No clear replacement of drive trains to reduce dependency on liquid fuels.
Key areas of development

BIOMASS

ALGAE
New land crops

HARVESTING

SEPARATION AND PRETREATMENT

Simple Sugars
Polysaccharides
• Starch
• Cellulose
• Hemicellulose
Lignin

Lipids

THERMAL PROCESSING

Hydrocarbons
Alcohols
• Ethanol
• Butanol

Hydrolysis

Fermentation/Catalysis

Pyrolysis oil

Hydrocarbons

Fermentation

Ethanol

Coskata Range Fuels

MeOH, DME, MTG, FT fuels

Choren Rentech

Virent LS9 Amerys

Gevo Mascoma Other

Saffire Aurora

Solazyme

and many more

Bio-SPK

Fatty acid methyl esters

Cyclic hydrocarbons

Rentech

UOP

NESTE

COP

COP/ISU

GTI

Evergent

UOP

Other
Another biofuel dilemma… for the investors

Product Differentiation

Operational Efficiency

Technology driven

Commodity driven

High Margin

High Volume
Another biofuel dilemma: what is the business model?

- Technology driven
  - Second Generation Biofuel Companies

- Operational Efficiency
  - Commodity driven
"Voyages of discovery are made not by seeing new places but by having new eyes"

Marcel Proust